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Energy Spectrum of the March 1989 Forbush Decrease

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ABSTRACT

Energy Spectrum of the Primary Cosmic Rays based on the experimental data of the World Wide Network of the Neutron Component of the Galactic Cosmic Rays, during the Huge Forbush Decrease of the March 1989 was calculated.

Key words: *cosmic rays, Forbush effect, energy spectrum.*

Electromagnetic properties of the heliosphere

The discovery of cosmic rays more than 113 years ago opened new horizons for further understanding and studying of the laws of the mega-universe and astrophysics. The World Wide g Network of neutron monitors and meson telescopes located on the Earth's surface is a fairly effective and highly economical tool, which, first of all, requires knowledge of the physical processes occurring in the Earth's magnetosphere and atmosphere.

Scott Edward Forbush from the Carnegie Institution (Washington, DC, USA) in the 1930s, observing the intensity of cosmic rays with four identical ionization chambers located in Huancaya (Peru), Christ Church (New Zealand), Godhaven (Greenland), and Cheltenham (USA), discovered three types of temporal variations of primary cosmic radiation, which appear on completely different time scales: a) an increase in the intensity of cosmic rays caused by solar flares lasting minutes and hours, b) the Forbush decrease of cosmic rays, the so-called Forbush decay, which lasts for hours and days, and which was later called the Forbush effect, and c) large-scale (11-year) changes in cosmic ray intensity [1].

The Forbush decrease is one of the two largest [2] and most significant transient changes observed in cosmic ray intensity, the other being the increase in cosmic ray intensity caused by a solar flare. Typically, cosmic ray intensity during a [8]. Forbush decrease reaches a minimum value of the observed cosmic rays intensity for a few hours, and then begins a gradual recovery to its previous value, often slowly, over several days. Sometimes, but rarely, a second decrease occurs even before the first recovery is complete. Often, but not always, a Forbush decrease occurs after a cosmic ray increase caused by a solar flare. Also, Forbush decreases in cosmic ray intensity are often, but not always, associated with geomagnetic storms. Geomagnetic storms, in their turn, are usually associated with shock waves propagating through interplanetary space [2].

The majority of works devoted to the study of cosmic ray intensity Forbush effects have adopted the idea that cosmic ray Forbush effects represent a certain reflection of the geometric structure and physical parameters of shock waves and magnetic clouds arising from chromospheric flares on the Sun and variations in cosmic ray intensity. The existence of plasma clouds coming from the Sun to the Earth was not known for a long time before the discovery of the solar wind [3,4]. To explain geomagnetic storms, the idea of the existence of magnetic fields frozen in the plasma, according to which its propagation should occur along the lines of force of the solar magnetic field [5], was later proposed. This idea was later developed by various authors, and the reason for the Forbush effect in the intensity of cosmic rays was mainly believed to be the scattering of charged cosmic particles by the magnetic field of the plasma cloud, which should have a turbulent character [6] and the shape of a smooth loop [7], or even the shape of a magnetic tongue [8].

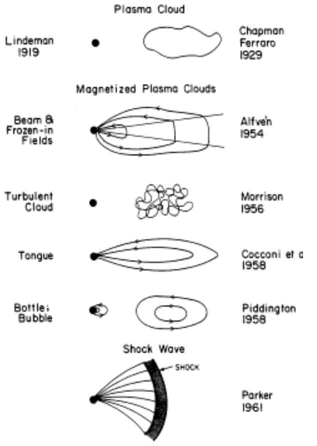

Fig. 1. Various possible configurations of Interplanetary Structures considered to be responsible for Forbush Decreases of Cosmic rays.

Fig. 1 shows the development of the basic ideas about the structure of turbulent magnetic phenomena, before the introduction of the concept of a shock wave [9,10] and the strict definition of the properties of a magnetic cloud. The concept of a magnetic cloud [11 -14] was introduced to describe such structures of the solar wind, which have an enhanced flow of magnetic field intensity. Which rapidly changes its direction at a large angle under conditions of low plasma temperature. Most of such structures have been observed after the passage of shock waves. It is now believed that magnetic clouds represent a certain variety of eruptions, its specific type, in interplanetary space [11,15] Fig. 2 [15,16].

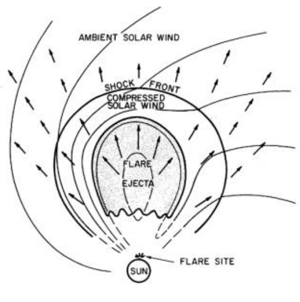

Fig. 2. Magnetic Clouds

A large series of recently published papers has focused on the contribution of magnetic clouds to the decline in cosmic ray intensity. In some works [11], the decrease in cosmic ray intensity was attributed to turbulent magnetic fields between the shock wave and the associated magnetic cloud. The correctness of such ideas is supported by the observation that the beginning of the decrease in cosmic ray intensity coincides with the moment of passage of the shock wave and the decrease process continues after the magnetic cloud, and that magnetic clouds without shock waves are associated with a small or insignificant decrease in cosmic ray intensity [11, 17].

Before entering the Earth's magnetosphere and atmosphere, cosmic rays of galactic origin pass through an area of space that is constantly under the influence of all solar activity, called the heliosphere (its boundaries are quite close to the dimensions of interplanetary space). Therefore, the study of cosmic ray variations requires an analysis of the physical processes that take place within the heliosphere, and, of course, on the Sun. Therefore, before moving on to the study of the Forbush effects, let us briefly review the physical processes taking place in the heliosphere and on the Sun.

It can also be noted that the solar wind, whose influence is characterized by the [8]. modulation of galactic cosmic rays, is gradually becoming the subject of heliosphere studies. [18, 19].

On the other hand, the use of information obtained by artificial Earth satellites and various space vehicles is statistically unjustified due to the small number of their localization sites. And Forbush effects, especially grandiose ones, such as those of July 1959 [20], August 1972, March 1989 and March 1991, reflect more completely and on a global scale the physical processes occurring inside the heliosphere. Therefore, experimental and model studies of Forbush effects are the only powerful tool that allows us to understand on a global scale the physical processes that took place in the heliosphere during the course of a particular Forbush effect.

Characteristics of solar activity and solar wind

The most obvious manifestation of the solar activity cycle [21] is the number of sunspots and the area of sunspots. Therefore, the term sunspot cycle is always used synonymously with the solar cycle. The duration of the period varies somewhat from one cycle to the next, but on average it is 11 seconds. The beginning of a new cycle is taken to be the moment when the number of sunspots is minimal [21].

In order to follow the development of the solar activity cycle, it is most convenient to observe how the number of sunspots that form on the Sun changes over time. The temperature of sunspots is, on average, 200–300 degrees lower than that of the surrounding photosphere [22], so they appear as black spots on a white background.

A universal indicator of solar activity is the Wolff number R. It is calculated by the formula: $R = K(10g + f)$, where f is the number of individual spots, g is the number of groups of spots, and K is a correction factor that is selected individually to take into account the characteristics of the instrument, the environment, and the person [21, 24]. The factor 10 is somewhat arbitrary. It is believed that the effect of a group of spots is much more effective, about 10 times, (for example, on the Earth's magnetic field), than that of individual spots [25].

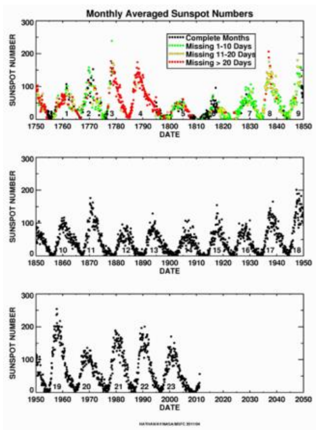

Fig. 3. Daily values of the sunspot Wolff number

Based on the analysis of daily values of the sunspot Wolff number (Fig. 3), it has been established that the cycle periods are less than 11 years long, among which the 28-day changes in the sunspot Wolff number are very important. They are caused by the rotation of the Sun around its axis, as they are associated with the helio-longitudinal asymmetry of solar activity [21,24]. Solar activity is accompanied by corresponding changes in the intensity of cosmic rays. An excellent example of this is the 27-day variations in cosmic rays intensity [26, 27, 28].

There are also periodicities with a duration longer than 11 years. The most important of these is the 22-year periodicity, called the Halley cycle. It is associated with the reversal of the Sun's magnetic poles. It should be noted that the 11-year cycle is not exactly periodic, but rather quasi-periodic [24].

The so-called flares observed on the visible disk of the Sun are the result of a sudden (transient) release of energy from the Sun's core into the Sun's atmosphere (mainly the chromosphere and corona). Solar flares cause, first of all, localized and temporary heating (thermal flares), and then the acceleration of electrons, protons, and premature heavy ions (particle flares). The temperature in the chromosphere reaches 104 K (chromospheric low-temperature flares). The temperature in the corona reaches 107 K (coronal or high-temperature flares). The energy of the ejected particles varies from 20 GEV to 1 TEV. The energy released in the largest flare is 10^{32} ergs [21,24,25]

Solar flares produce transient electromagnetic radiation, in a very wide energy range, from hard X-rays to radio radiation of wavelengths of several kilometers ($10^{-9} – 10^{6}$ cm), the radiation is mostly thermal in nature [21, 24].

Flares are closely associated with active regions: the majority are observed in young and mature active regions; large flares, in particular, occur in regions with large vortices, complex magnetic field configurations, and large field gradients [25, 29].

The most efficient event occurring in solar active regions is the conversion of a significant amount of energy ($10^{32} – 10^{33}$ ergs) in a relatively short time ($2 \cdot 10^{3}$ seconds) [29]. Such an event can be called a solar storm [29]. The optical manifestation of a solar storm is a sudden increase in the brightness of the Balmer series H_{α} line. This specific event is called a solar flare [29]. It is also often observed as intense X-ray, ultraviolet, and radio emission. During some flares, the brightness of the continuous spectrum increases over the entire region of the flare, even in the visible region of the spectrum. Solar storms also cause various dynamic processes in the solar atmosphere. Shock waves are generated, which then propagate in the solar wind plasma. Some of them overcome the Sun's gravity and extend beyond the Earth's orbit [29].

Five types of radio emission (I–V) are known [29]. The most remarkable and long-lasting type of radio emission is type IV. This emission usually lasts for several hours after the optical flare. It is believed that this type of radio emission contains both synchronous and plasma emission. Wild [30] has shown that this emission sometimes originates from the active region [29].

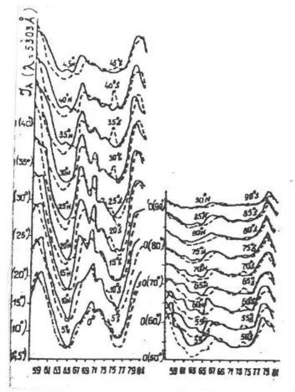

Fig. 4. Coronal green line for each 5° zone of the northern and southern solar hemispheres [31].

Fig. 4 shows the time course of the coronal green line for each 5° zone of the northern and southern solar hemispheres [31]. During the period 1957–1981, this allows us to identify heliogenomic features of the the 10^{-th} and 21^{-st} cycles in different hemispheres, which are also characteristic of other indices. For example, such as the double peak of the 20th cycle maximum, the "slippage" of activity to lower latitudes as the cycle progresses, and the predominantly high activity in the northern hemisphere. In addition, it is also possible to observe some of the characteristic features of the cyclic changes in solar activity that are characteristic only for this index and are indicated [32] at high latitudes (<45°) In the absence of a minimum in 1969-1971 (in these areas the line brightness increases 1- 4 years before the magnetic activity minimum at low latitudes), the areas of increased brightness of the coronal green line slowly, over 4-6 years, shift towards the poles, and disappear during the maximum of the spots. If we consider that the change in the magnetic cycle of the poloidal field can be traced according to the change in coronal activity, then this delay indicates an increase in the poloidal component at high latitudes, at a time when it is minimal at low latitudes. i.e. the poloidal field is maximal when the toroidal one has a minimum of activity [33]. The fields in the northern and southern hemispheres are often quite similar, and the inversion does not occur simultaneously. Obviously, if the assumption that the solar activity data we use (the area of the spots S and the intensity of the coronal green line I_{λ}) reflect the changes in the various components of the solar magnetic field over a 22-year cycle is justified, then this relationship is most clearly confirmed by the figure, which shows the changes in S and I_{λ} during the course of the field inversion for both hemispheres of the Sun [31].

The analysis of the changes in the area of sunspots and coronal activity in different hemispheres and the change in the sign of the solar total magnetic field, carried out for the 19^{-th}-21^{-st} solar activity cycles, allows us to draw the following conclusions: 1) the change in the sign of the solar total magnetic field observed on the solar disk is reflected in the change in the intensity distribution of the coronal green line; 2) the inversion, starting in one of the hemispheres of the Sun, leads to the achievement of the maximum intensity in the coronal green line radiation. In addition, it should be noted that the correspondence between these phenomena is observed only if the coronal radiation is considered in the entire hemisphere, and not in its separate latitudinal zone [31].

Investigation of the Forbush effect of March 11-25, 1989

The classification of the Forbush effect [34 – 37] showed that the change in the energy spectrum of the Forbush effect over time obeys certain regularities. It is interesting to single out a case when the energy spectrum of the Forbush effect is soft during the period of the cosmic ray intensity minimum ($\gamma = 1.2 - 1.5$), and then, over time, hardens and becomes hard at the end of the Forbush effect ($\gamma = 0.2 - 0.4$). Such a change in the energy spectrum of the Forbush effect was described in the works of M.V. Alania and his co-authors [34 – 42] , and also in the doctoral dissertation of M.V. Alania. [43]. In particular, these works show that the time broadening of the energy spectrum of the Forbush effect should be related to the emergence of new, large-scale magnetic inhomogeneities in interplanetary space as a result of the interaction of the shock wave and the background solar wind.

These large-scale magnetic inhomogeneities cause an increase in the magnetic field strength fluctuations of interplanetary space, in the frequency range $f = 10^5 – 10^6$ Hz, which is accompanied by an increase in the power spectral density (PSD) of the fluctuations of the magnetic field inhomogeneities in interplanetary space, ν, which in turn leads to a decrease in the power spectral density of the energy spectrum of the isotropic intensity variations of cosmic rays, γ.

Naturally, the question arises whether the energy dependence of the energy spectrum of cosmic ray variations, γ, also occurs in Forbush effects, as this has been shown for the energy spectrum of 11-year cosmic ray variations [44 – 52]. For this purpose, several Forbush effects should be studied, and as an example, we will consider the Forbush effect of March 11-35, 1989, in detail.

Heliospheric and magnetospheric events in March 1989

The first and most energetic series of solar activity cycle 22 began with the appearance of an active area near the eastern limb of the Sun, AR 5395 [2]. From 6 March 1989, a moving active area, AR 5395, appeared on the visible disk of the Sun. Even before this area became visible, it was possible to observe how the upward activity spread from the limb. The corresponding sunspot area itself was rotating inside the Sun. By 6 March 1989, it was located at 34° of the northern heliolatitude, which is a very high heliolatitude for such a large sunspot group [53]. The sunspot configuration was very complex, with well-defined spots of opposite polarity located close to each other. There were several notable energetic solar events as the center of activity moved across the solar disk. This included an event on March 6, during which the GOES X-ray monitor indicator went off scale; it was rated as an X15-class X-ray event. On March 9, X4 and 4B (strong X-ray and optical emission at the same time) events were observed. On March 10, an X4.6 and 3B class event occurred, which is believed to have triggered the geomagnetic storm of March 13, which had the largest aa (24-hour aa index) in the last 120 years. According to the criterion of X-ray emission productivity observed to date, the active region AR 5395 was the most productive of the active regions observed in the last 15 years [54].

On March 13, 1989, at 09:30 UTC, the global network of cosmic ray stations around the Earth recorded a grandiose Forbush effect, the second largest in amplitude (27.20%) after the Forbush effect of August 1972. It began with the arrival of an interplanetary shock wave [2].

The change in the number of sunspots clearly indicates the fact that since September 1986, an 11-year cycle of solar activity began. Usually, by this time, the intensity of cosmic rays has reached another peak, and has begun to decrease further, and by March 1989 it had decreased to 90%. According to neutron monitors (located on the Earth's surface). The active area AR 5395 began to rotate on the visible disk of the Sun since March 6, 1989. It was a very active area, and was accompanied by several bright flares. During the two weeks during which the process of crossing the visible disk of the Sun by the active area AR 5395 continued, the onset of a geomagnetic storm was recorded five times at different times, with its sudden onset, which, as a rule, is expressed, in each individual case, i.e. at all five times, the fact of the arrival of a shock wave propagating in interplanetary space to Earth has been recorded. Such cases occurred at the following moments in time:

1) March 8, 17:55 UTC; 2) March 13, 01:27 UTC; 3) March 13, 07:43 UTC, ~ 450 γ; 4) March 16, 05:34 UTC; 5) March 19, 04:23 UTC; [55]. In addition, there is also a signal of a large shock wave reaching the Earth (~ 450 γ), at one of the geomagnetic stations, March 13, 07:43 UTC.

Investigation of the Forbush Effect of March 11-25, 1989 (continued)

Fig. 5 shows the change in the intensity of cosmic rays during the Forbush Effect of March 1989. This figure shows that the minimum of the intensity of cosmic rays is observed at different times at different stations, which is obviously associated with the numerous flares on the Sun that occurred on March 9-10. The energy spectrum of cosmic rays, based on the data of all stable and well-functioning neutron monitors of the World Wide Web, is shown in Fig. 6 Analysis of the results obtained shows that during the period of decrease in the intensity of cosmic rays, on March 13-14, the energy spectrum is relatively soft. In the following period. This case can be considered as one of the good examples of the Forbush effects, when convection intensively removes low-energy particles, and at the same time, due to the reflective properties of the shock wave or magnetic cloud, it is difficult for mainly low-energy particles to penetrate into the inner region of the magnetic cloud or shock wave. In both cases, the energy spectrum of the isotropic intensity variations of cosmic rays should be relatively soft, which is clearly seen from the given figure.

From March 15 to March 24, the energy spectrum of the isotropic intensity variations of cosmic rays is relatively rigid, which indicates that as a result of the interaction of the shock wave and the background solar wind, a structure of interplanetary magnetic field strength fluctuations was formed, when the density characteristic of the energy spectrum of these fluctuations is index $\nu = 1.5$, almost up to a frequency of $f = 10^6$ Hz.

In order to determine whether there is a dependence of the cosmic ray energy spectrum characteristic γ on the magnetic hardness R of cosmic ray particles, the neutron monitors of the World Wide Web were divided into two groups:

1) the first group includes neutron monitors of the World Wide Web in the cutoff threshold range from 0 to 7 GV;
2) the second group includes neutron monitors of the World Wide Web in the cutoff threshold range above 7 GV.

The change in the energy spectrum characteristic γ of the Forbush effects of cosmic rays with time is given in Fig. 7 and Fig. 8 respectively. These figures show that the energy spectrum of the Forbush effects of cosmic rays according to the data of the first group (low energies) stations is softer than that of the second group (high energies). This is especially clearly observed for the period from March 13 to 16. Therefore, there is actually a tendency, even during the Forbush effect, for the energy dependence of the energy spectrum characteristic of the isotropic intensity variations of cosmic rays, γ. The latter once again confirms the proposition [120] that the characteristic γ of the energy spectrum of isotropic intensity variations of cosmic rays well describes the dynamical-structural change (change in γ) that occurs in fluctuations of the interplanetary magnetic field strength.

Therefore, the change in the energy spectrum characteristic of cosmic ray Forbush effects, γ, with time, allows us to study the integral changes in the interplanetary magnetic field strength fluctuations after solar flares, which are mainly sources of interplanetary shock waves and magnetic clouds.

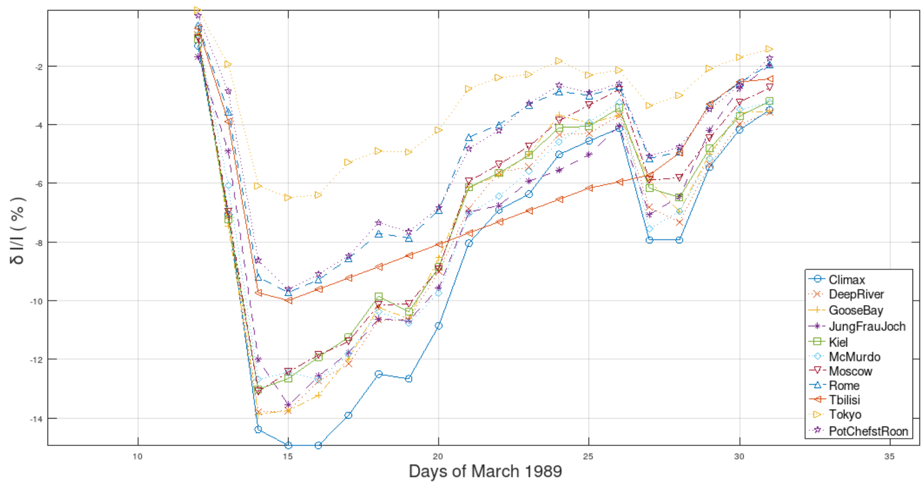

Fig. 5. Cosmic Rays Intensity Changes during March 1989 Forbush-Decrease

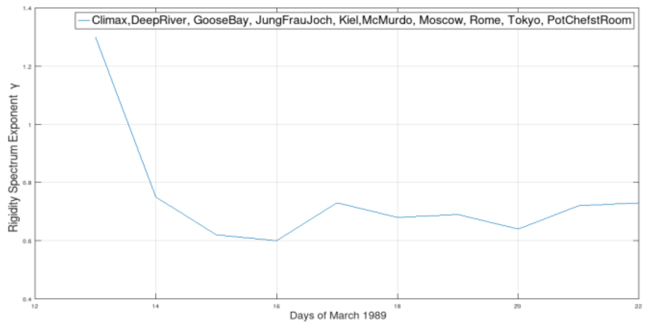

Fig. 6. The energy spectrum of cosmic rays, based on the data of all stable and well-functioning neutron monitors of the World Wide Web

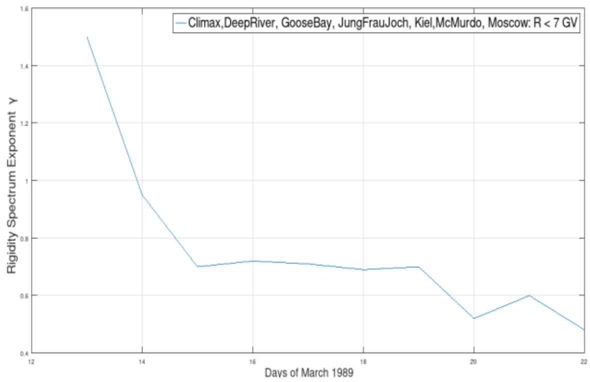

Fig. 7. Energy spectrum of the Forbush effects of cosmic rays according to the data of the first group (low energies)

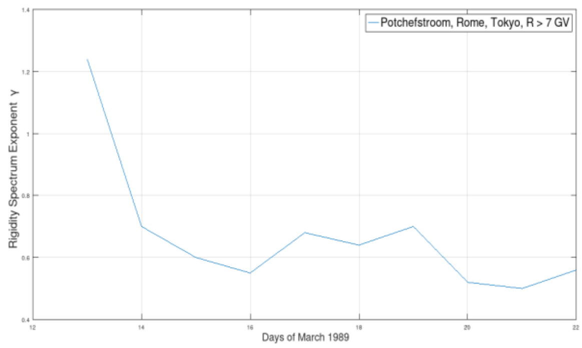

Fig. 8. Energy spectrum of the Forbush effects of cosmic rays according to the data of the first group (high energies)

Conclusion

The energy spectrum of the Forbush effects of cosmic rays according to the data of the Neutron Monitor data with the lower CutOff Rigidity is softer than that of the second group Neutron Monitor Data with the higher CutOff Rigidity

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1989 წლის მარტის ფორბუშ ეფექტის ენერგეტიკული სპექტრი

ე. ალანია, თ. ბოჭორიშვილი, რ. ასლამაზაშვილი, თ. ბაქრაძე, ნ. ღლონტი, თ. ერქომაიშვილი, ა. ბელოვი, ვ. იანკე, რ. გუშჩინა, ე. ეროშენკო, ა. ვავრზინჩაკ-საბანი, გ. ვანიშვილი

რეზიუმე

კოსმოსური სხივების ფორბუშ ეფექტის ენერგეტიკული სპექტრი, დაბალი მოჭრის ზრურბლის მქონე ნეიტრონული მონიტორების მონაცემების მიხედვით არის რბილი, ვიდრე მაღალი მოჭრის ზღურბლის მქონე ნეიტრონული მონიტორებიდან მიღებული მონაცემების შემთხვევაში.

საკვანძო სიტყვები: კოსმოსური სხივები, ფორბუშის ეფექტი, ენერგიის სპექტრი.

Энергетический спектр Форбуш-эффекта в марте 1989 года

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Резюме

Энергетический Спектр Форбуш-эффекта космических лучей, согласно данных, полученных от станций нейтронных мониторов мировой сети, с низким уровнем жёсткости магнитного обрезания является более мягким, чем в случае нейтронных мониторов, с высоким уровнем обрезания жёсткости.

Ключевые слова: космические лучи, эффект Форбуша, энергетический спектр.